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No. 401

THE HEAT TREATMENT OF DURALUMIN

By Lieut. Comdr. Wm. Nelson, (CC), U.S.N.

From "Aviation," February 21, 1927

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THE HEAT TREATMENT OF DURALUMIN.

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General

When certain light aluminum alloys are heat-treated, quenched and aged, there is considerable improvement in their tensile properties. This remarkable phenomena was first discovered in the case of duralumin by Wilm and has been described at length by him and by others.

When duralumin is heated to a temperature of about 500°C, and quenched in water, there is a period immediately after the quenching when the material increases in hardness and tensile strength with time. After several days the duralumin attains relatively constant hardness and tensile properties. This period after the quenching is known as the aging period and the material is said to be aging or maturing. It is this feature that places it in a different category from the steels in so far as heat treatment is concerned.

Duralumin is a high strength aluminum alloy and attains that classification through its heat treatment much in the same way as the high strength steels attain their properties through correct heat treatment. And although other aluminum alloys can

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be heat-treated to produce desirable characteristics, duralumin is outstanding in its variety of practicable uses through the particularly good qualities obtained by relatively simple treatments.

Cast duralumin responds somewhat to heat treatment, but the form in which this alloy is used is as a wrought product, so our discussion will be confined to the latter. It is supplied in strip, plates, angles, special shapes, tubes, forgings, etc., and all respond to the same heat treatment practices.

There are two very useful heat treatments given to duralumin, namely, annealing, and heat treating to produce the high physical properties for which this alloy is outstanding. To avoid confusion, the term "annealing" will be used to mean the softening of the material to put it in the best state for cold working. To keep duralumin soft and workable over a period of time and to attain the greatest amount of softness for all forms of cold working, it can be annealed by heating to about 350°C (662°F) and allowing it to cool in air. The term "heat treating" will be used to mean the heating of duralumin to a temperature sufficient to bring out the best tensile properties by subsequent aging. The heat treating temperature of duralumin is 490°C to 510°C (914°F to 950°F). These two treatments are used very frequently in the manufacture of duralumin products, and in order to obtain results that are consistent, the temperature control must be accurate.

The physical properties of duralumin in these standard tempers and in an unaged temper are given as follows:

Condition of material	Tensile strength lb. per sq.in.	Yield point lb. per sq.in.	Elongation % in 2 inches	Scleroscope hardness
Annealed	25-35000	9-10000	10-14%	9-12
Heat-treated and aged	55-63000	30-36000	18-25%	23-27
Heat-treated and unaged	46-52000	--	18-25%	10-13

Theoretical Discussion

When duralumin is normalized after any initial wrought condition by heating to 500°C (932°F) and cooled in water, oil, or air, the material is in a relatively soft condition, resembling annealed metal. However, as the alloy is allowed to stand at room temperature, it increases in hardness and tensile strength rather rapidly, eventually reaching a point where the increase is not great for protracted periods of time. This peculiarity of aging has caused considerable discussion among metallurgists and has been investigated extensively to determine the exact cause. The theories on which the hardening with time is based are complicated, to say the least. Duralumin aged at very low temperatures, such as that of liquid air, does not harden with age. It is therefore an opinion that the aging process is a heat treatment that takes place at room temperature.

Before going to the chemical metallurgical phases of the heat treatment process it is proposed to discuss the effect on the physical properties brought about by varying the temperature of heat treatment, the temperature of quenching, and the period of aging.

Duralumin sheet as it comes from the rolls has a tensile strength of 38-48000 lb. per sq.in., with an elongation of about 2% in 2 inches. These values, of course, depend on the reduction made in the sheet and are therefore only representative. However, it is from this approximate condition that the final properties are produced.

In Fig. 1 there are shown the ultimate tensile strengths, elongations, and hardnesses obtained from duralumin sheet heated at varying temperatures, quenched in boiling water, and aged about five days. The material used was initially in the heat-treated state, giving the values obtained below 300°C (572°F). There are two points on the tensile strength and hardness curves of particular interest. These are the low values obtained by heating to about 330°C (608°F), and quenching, and the high values obtained by heating to 500°C (932°F), and quenching.

The effect of heat treating up to about 350°C (662°F) is to produce a relatively soft material. From 350°C up to 520°C (662°F to 968°F) the hardness increases with increase in the heat treating temperature, so that practically any desired hard-

ness can be produced in duralumin by heating to a determined temperature, quenching, and aging. Above 520°C (968°F) blistering of the metal occurs, indicating the approach of the melting point. Blistering will occur in some duralumin below this temperature but it is believed to be due to the constitution of the particular pieces that act in that way rather than being representative. To produce the best results the heat treating temperature should be high enough to insure the solution of the magnesium-silicon and copper-aluminum compounds and that temperature is about 490°C to 510°C (914°F to 950°F).

It is natural to suppose that variations in the medium used for quenching and the temperature of that medium may cause different results. However, there apparently is little or no effect on the physical properties produced by varying the temperature of quenching within the ranges tried. It has been noted, however, that quenching to a low temperature, say 10°C , ^(50°F) that the metal is softer immediately after the quench than is the case where higher temperatures have been used. The ordinary quenching mediums are air blast, water, and oil. The physical properties resulting from an air blast quench are slightly less than those obtained by a liquid quench. Oil and water produce about the same results. The reasons for using various mediums for quenching is dependent on the working of the metal to be done and on its relative ability to resist corrosion.

Two factors come into the aging process, namely, temperature of aging and time of aging. In Fig. 2 there are given curves showing the effect of aging on the physical properties. These curves have been corroborated by several investigators so there is little left to be questioned regarding their form. Quenching at 100°C (212°F) and aging at room temperature seems to accelerate the aging process. It has been noted that the rate of hardening increases as the temperature of aging increases; that the maximum hardness is obtained by aging at temperatures above 100°C and that at aging temperatures above 140°C (284°F) the hardness eventually drops after reaching its maximum.

Aging is practically complete after about four days although there is reason to believe that some changes take place for very long periods over that. During the early part of the aging period it is practicable to work duralumin rather extensively without impairing the material. This factor is taken advantage of in various ways, some of which will be described below.

The chemical composition of duralumin is given as follows:

Copper,	3.5 tp 4.5%
Magnesium,	.4 to 1.0%
Manganese,	0 to .7%
Iron,	.4 to 1.0%
Silicon,	.3 to .6%
Aluminum,	remainder.

This combination permits of a variety of possibilities in the final product making the chemical-metallurgical theory uncer-

tain. The effect of adding small quantities of other metals such as nickel, tin, chromium, etc., is not great and can, in general, be disregarded.

The binary alloys formed in duralumin and to which the effect of heat treating and aging are ascribed, are Mg_2Si and $CuAl_2$. Alloys which contain only the copper-aluminum group, show very little aging effect but do show an appreciable hardening effect. Likewise, the alloys containing the magnesium-silicon group without the copper, show marked aging effect. It is therefore possible that the $CuAl_2$ produces the initial hardness when heat-treated and quenched and that Mg_2Si produces the increase in hardness during aging at room temperature, by dissolution of these constituents.

Considering first the compound $CuAl_2$ and its effect on the initial hardness. Tests conducted at the Bureau of Standards places the solubility of $CuAl_2$ in aluminum at 4% at $500^{\circ}C$ ($932^{\circ}F$), and 1% at $300^{\circ}C$ ($572^{\circ}F$) by quenching. Accordingly, if the temperature is reduced slowly from $500^{\circ}C$, the $CuAl_2$ that was in solution will precipitate in a highly dispersed form, resulting in duralumin that is relatively soft. Now if the temperature is reduced from $500^{\circ}C$ rather rapidly, as by quenching, the $CuAl_2$ is held in part in solution, producing a relatively hard alloy. Now if the metal is held at room temperature over a period of time the $CuAl_2$ tends to precipitate bringing about equilibrium. This precipitation is un-

doubtedly in the form of very finely divided particles. If the duralumin is aged at a low temperature ($-180^{\circ}\text{C} = -282^{\circ}\text{F}$), the hardening does not take place, due undoubtedly to the absence of any precipitation. The annealing is assumed to result from the coalescing of the finely divided particles of CuAl_2 .

Theorists differ on the relative importance of CuAl_2 and Mg_2Si in duralumin. The Mg_2Si acts in very much the same way as has been described for CuAl_2 if that is the constituent producing the effect, so for all practicable purposes each is a necessary compound, producing its effect by precipitation in a dispersed form. However, increasing magnesium beyond that necessary to take up all the silicon reduces the solubility of the Mg_2Si at the higher temperatures.

The manganese in duralumin makes for better mechanical properties and although it may have a part in bringing out the hardening effect of CuAl_2 , its addition beyond 1% makes bending and forming difficult.

A balance between the various elements undoubtedly exists and has in a way been investigated physically and metallographically. However, within reason, the quantities given above seem to produce the most desirable qualities for the simple heat treatments used in practice.

Heating Apparatus

Heating of duralumin for heat treatment may be done in a furnace or in a salt bath. The primary requisite that the material be heated uniformly on all sides, is the main function of the apparatus. The use of an open flame for heating is not satisfactory on account of the nonuniformity obtained by such means.

The use of a salt bath is perhaps the most common method in vogue. It has the disadvantage that thorough washing off of heat-treated parts is necessary after heat treatment to insure that no salts are left on the duralumin. It has the same disadvantage over a furnace for parts which are to be worked hot. Salts left on duralumin tend to hasten corrosion.

The tank for containing the salt bath is made of a size dependent on the material to be heat-treated. For ordinary medium size pieces a tank 4 x 3 feet and 3 feet deep, is convenient. For longer pieces, a long tank about 2 feet wide and 4 or 5 feet deep is most suitable. The tank is built up of 1/2 inch or 3/4 inch mild steel plates, calked and otherwise made water-tight. Built around the bath and acting also as a foundation for the tank, is a brick furnace. This furnace can be heated by electricity, oil, or gas. Coke, coal, or charcoal furnaces are not used owing to the formation of explosive mixtures when carbonaceous fuel gases come into contact with nitrates. The necessary features of the furnace are a

uniformity of temperature in all parts, a ready control of the temperature by the operator, and an equalization of heat distribution around the bath. In cases where deep tanks are used baffles must be arranged around the furnace to keep the flames from making direct contact with the tank, and in all cases the baffles should be so arranged that the salts will begin to melt along the side near the top so that relief will exist for expansion of the salts.

The salt bath is composed of approximately equal parts of sodium nitrate and potassium nitrate (commercially double refined). In adding salts to the molten bath, care should be exercised as the presence of moisture causes spattering of the liquid. The usual procedure is to add salts when the bath is cold. The melting point of this bath is about 260°C (500°F). It is possible to use sodium nitrate alone but since material becomes coated with a salt crust after having been immersed in such a bath, it is better practice to use sodium nitrate and potassium nitrate.

A platform should be provided around the furnace at the height which will make it convenient to handle the material being heat-treated into and out of the bath. Cranes and such other equipment as are necessary for handling the charges, should be considered. In order to avoid any damage to the parts, means must be provided for supporting the duralumin after heat treatment since it is easily distorted and bent by its

own weight while hot. Baskets made of strip or wire mesh serve the purpose well. They are also convenient for the quenching operation.

A very convenient means for handling rivets is to use a tube blanked at one end and long enough to submerge about $1\frac{1}{2}$ ft. into the bath. This also avoids placing the rivets in direct contact with the salts while being heated. Appliances used about a galvanizing plant find ready use in a heat treating plant for handling material, etc. Covers for the baths allow a bath to be heated up quickly when desired.

The pyrometric equipment is perhaps the most important installation. In a small bath one pyrometer is considered sufficient, whereas in a large bath two or three may be essential. All pyrometers should be permanent installations and should be of the recording type. The necessity for accurate temperature control is so important with duralumin that all practicable means to insure no deviations should be employed. A check on the pyrometers should be made weekly and no error in excess of 10°F should be permitted. Slight errors in the temperatures may cause very undesirable results.

The salt mixtures are kept at the temperature ranges used for annealing or heat treating duralumin. In order to avoid changing the temperature of a tank to suit both the annealing and the normalizing temperatures, it is the practice to keep one long tank and one small tank at the heat treating tempera-

ture, and a medium size tank at the annealing temperature. This arrangement will meet most conditions. Another means for avoiding the raising and lowering of temperatures for short periods is, to do the annealing at night and the heat treating during the day, using one bath for both operations.

The quenching tanks are of wood or steel. Steam coils or other means must be provided for controlling the temperature of the quenching medium. These tanks are of the same size as the salt bath, and are fitted with the usual accessories, such as inlet, overflow, and drains. They are fitted with platforms to facilitate operation and are located conveniently to the heat treating furnaces, so that quenching can be done immediately after heating. Baskets, tubes, etc., which are used for heat treating and quenching should be dry before they return to the salt bath on account of dangers to the operator through spattering of salts when moisture comes into contact with the salt. Some salts are carried over to the quench from the heat-treating tank, the only effect being to raise the boiling point of the water.

On account of the suspicion that attaches to the corrosion of duralumin which has been heat-treated in salt baths, there has been a tendency to turn to the use of electric or oil furnaces for heating this material. For long pieces, the electric tube furnace with quench tanks immediately below, is perhaps the best. For other parts, the ordinary muffled or semi-muffled

electric furnace suits. Coils and circulating fans to insure a uniform temperature in all parts, is the major essential. These furnaces as a rule are fitted with automatic temperature control devices. Oil fired furnaces have been used with considerable success. The combustion chamber is on each side of the heating space with connection between the two at the top only. There is no reason why the oil furnace should not be very efficient excepting alone, the question of uniform temperature with accurate control.

Annealing

In order to keep duralumin soft enough to be worked cold it is annealed by heating to a temperature of 350°C to 380°C (662°F to 715°F) and cooled in water, air, or in the furnace. In this state it is "dead soft." This state results in all cases regardless of the initial temper of the material. The effect is permanent and the properties remain constant unless the metal is subjected to working or subsequent heat treatment. It is in this temper that the alloy is most plastic and subject to the easiest working. The annealed condition should not be confused with the best condition for hot working of duralumin for they may not be the same.

The length of time the metal is held at the annealing temperature and the length of time allowed for cooling, affect the degree of anneal. It is essential that the material be thoroughly soaked at the annealing temperature and cooled very slow-

ly to obtain the softest condition. For sheets and shapes less than $1/10$ inch in thickness the length of time to anneal in a salt bath varies from 10 to 30 minutes, whereas in a furnace, the period is from four to ten times as long. Heating the material longer and oftener than necessary apparently has no effect. Thick sections of duralumin should be heated long enough for complete soakage.

It is the usual practice to wash off in hot water, parts which have been annealed in a salt bath to remove all traces of the salt.

When in the annealed state duralumin can be drawn, stamped, formed, and otherwise worked until the metal becomes hard through mechanical working. Reannealing can be resorted to as often as is desirable to keep the material in condition for further working. After the completion of such working, heat treatment at the normalizing temperature restores the physical properties to high strength classification.

Heat treating duralumin at a temperature above the annealing temperature, tends to bring the material into a state where it indicates hardening and aging qualities. Care should therefore be taken to maintain the metal within the ranges specified.

It is not always necessary to anneal duralumin to put it in condition for working, for there are many operations which can be done during the aging period after heat treating at the higher temperature. This in such cases eliminates one of the heating operations.

Heat Treating

Duralumin is heat-treated for normalizing at 490°C to 500°C (914°F to 932°F). The material is held at that temperature for a period long enough to become thoroughly saturated. This period varies, depending on the thickness of the piece. The following formula can be used to determine this time for a salt bath.

Time in minutes = $60 \sqrt{\text{thickness in inches}}$. In the case of a furnace the time is dependent on the conditions - a uniform heat for 20 minutes being sufficient. It should be noted that duralumin heats up rather rapidly and that prolonged periods of heating do not materially affect the temper.

There is, however, one important consideration during the heat treating of duralumin that bears comment. During the period that the material is hot, it must be properly supported to avoid distortion due to sagging. The metal will of its own weight tend to sag and in all cases where the parts are large, whether heated in a bath or a furnace, special attention to the support must be given.

In furnaces due to unequal distribution of heat, duralumin will in some cases be burned. The material when so burned is irreparably damaged. Inspections of heat-treated parts must be done with care to locate such damaged duralumin to be certain that the finished product has the desired features.

Heat treating of a piece in sections should not be undertaken for the part between the cold end and the furnace or bath will be partially annealed

Heating duralumin in a nitrate bath colors the material in a variety of hues. This discoloration is superficial and is not an indication of defects nor any particular inherent properties.

The quenching is ordinarily done in water. Quenching in boiling water accelerates aging. Quenching in cold water leaves the material softer to start the aging process. Oil is also used as a quench in connection with duralumin heat-treated in a furnace. Air blast or still air cooling are effective to avoid distortions that might take place in water quenching. However, metal quenched in air shows slightly lower physical properties when compared with metal quenched in cold water. Parts which are to be worked subsequent to heating should be quenched in cold water, whereas parts which are not to be worked should be quenched in hot water or air.

The time between removal from the heating medium and the quench should be a minimum and unless an air quench condition is desired, this period should not exceed 1/2 minute.

All nitrates that collect on duralumin during heat treatment should be washed off in the quenching operation.

Immediately after heat treating at 500°C (932°F) and quenching, the alloy is soft and pliable, permitting a variety of fab-

ricating operations. This softness leaves the metal on aging so that after about an hour the hardness has reached a limit where further working is done with difficulty. However, by undertaking the bending or forming immediately after quenching the work can usually be done before complete aging. No further heat treatment is necessary to parts so worked unless the working has been severe.

Quenching in water or oil usually distorts duralumin, so that straightening and squaring are necessary. Any of this work required must be done soon after the quench, during the soft state of the metal. Warping or buckling does not usually occur during the aging, so any stretching or straightening done will be retained.

The early aging period permits the driving of rivets without annealing. Rivets in all sizes up to about 1/4 inch in diameter are heat-treated at 500°C (932°F), quenched in cold water and driven within an hour after the quenching. Rivets not used during this hour are usually returned for another heat treatment, and so on. No ill effects are known to be attributable to this repeated heat treatment, although the rivets do seem to drive easier after a number of heat treatments. Rivets driven after this heat treatment and allowed to age, attain the same temper throughout.

Material in the sheet form is supplied by the manufacturers in the annealed, heat-treated, or hard-rolled condition.

Shapes may be supplied in the extruded condition if specified. These various conditions cause confusion in both the stores and in the shops, and in a number of instances annealed material has been used where heat-treated material was required. Skilled workmen can spot the condition by its working properties, but bend tests combined with scleroscope hardness tests usually indicate the condition beyond a doubt. A scleroscope hardness test should be in the shop inspection routine for every piece of duralumin going into final assemblies.

Conclusions

Very little of a novel nature has come out on heat treating duralumin in recent years, and there is reason to believe that the practices are very nearly standardized. There is a leaning towards the use of electric furnaces for heat treating this alloy to reduce possible dangers of corrosion from the nitrate salts used in baths. This measure appears desirable but uniformity of heating and accurate control of temperature, both obtainable with salt baths, are very important factors.

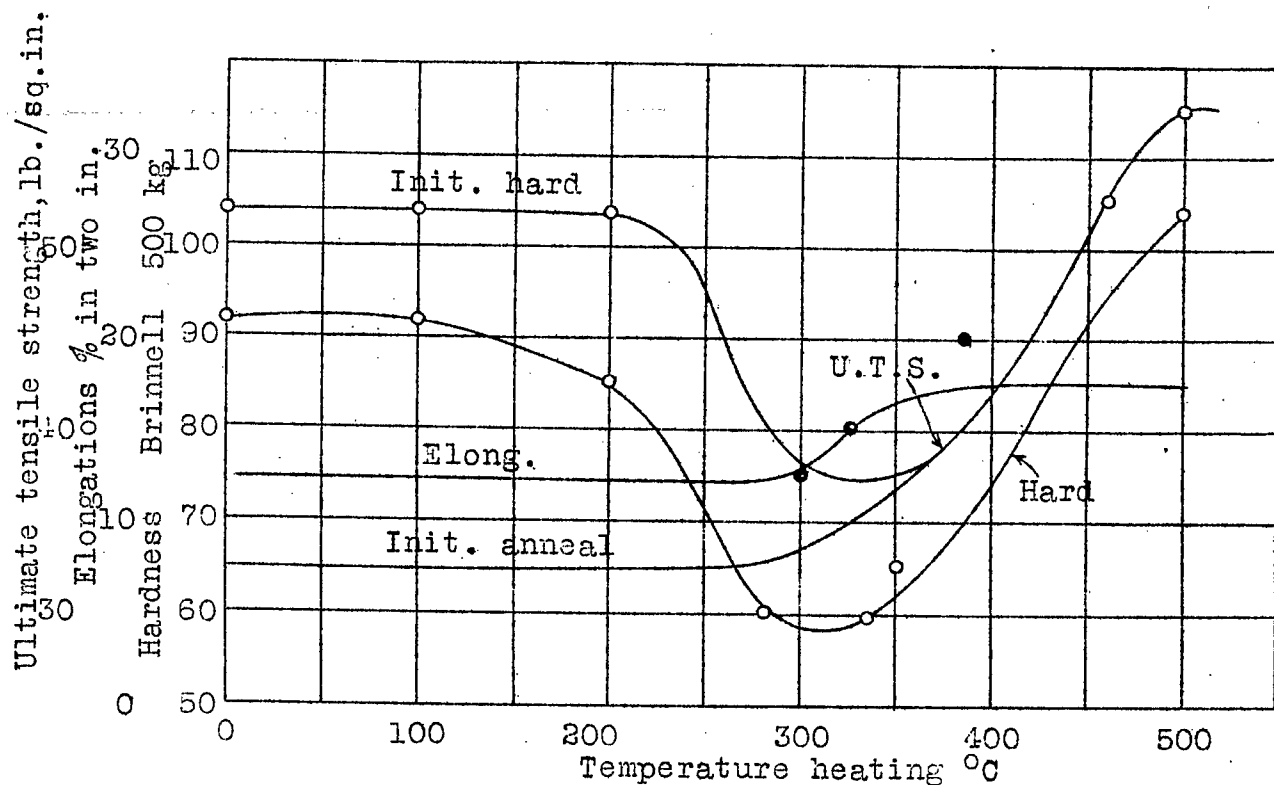


Fig. 1 Effect of heating duralumin to varying temperatures quenched and aged.

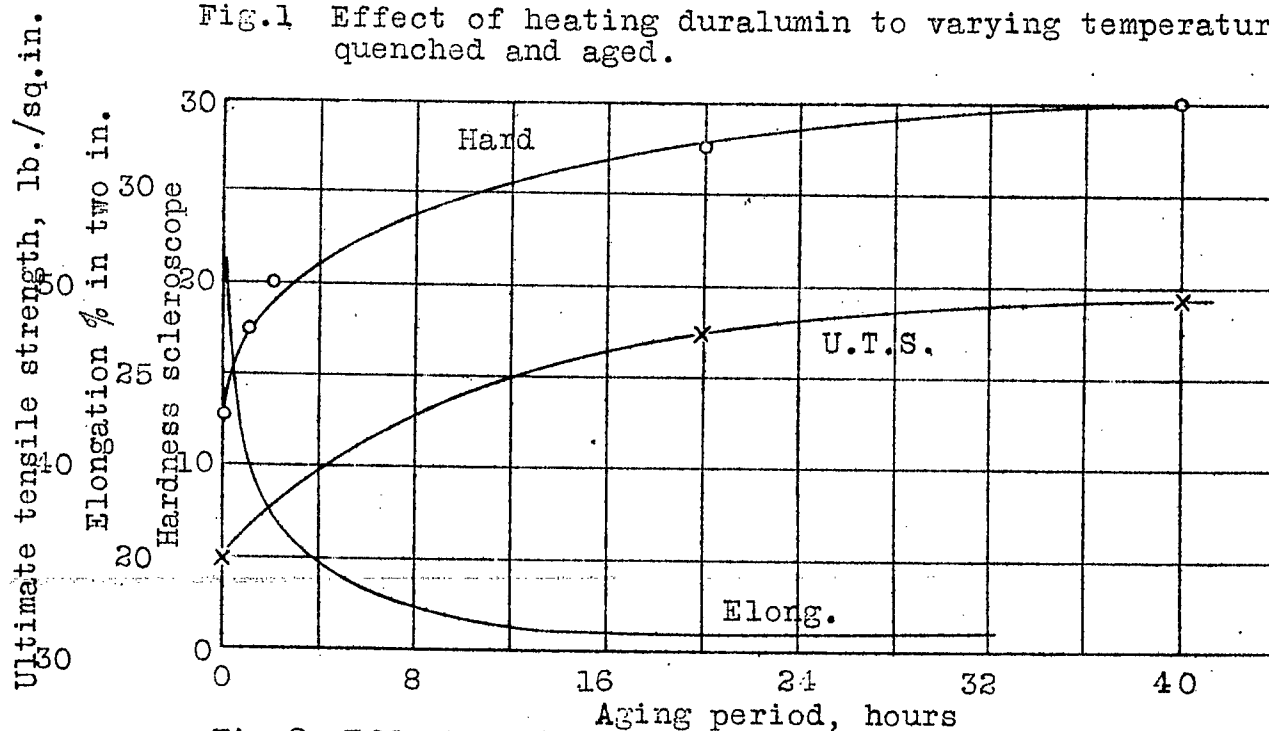


Fig. 2 Effect of time of aging duralumin. Heat treated and quenched from 500°C.

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